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Studying the excitation function for the astrophysically important nuclear reaction ^{26}Mg(p,n)^{26}Al

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***Abstract*—^{26}Mg(p,n)^{26}Al nuclear reaction is an exciting way to produce astrophysically important ^{26}Al nucleus. Insight to this reaction can give us deeper understanding of ongoing nucleosynthesis process. The yield of ^{26}Al varies with the energy of the proton that are incident on the ^{26}Mg nucleus. The variation of yield with incoming projectile energy is known as excitation function. There is lack of sufficient data for this excitation function. The excitation function for the reaction ^{26}Mg(p,n)^{26}Al is calculated (for proton energy from 0 MeV to 30 MeV) using EMPIRE simulation and is then compared with the available data from NNDC database.**

Keywords— Excitation function, EMPIRE, nucleosynthesis, ^{26}Al isotope.

I. INTRODUCTION

In nuclear physics the term excitation function (or, yield curve) describes the dependence of a specific nuclear reaction's cross section on the energy of the incident particle. Yield curve provides valuable insights into the understanding of nuclear structure and dynamics of a nuclear reaction and is of immense importance to areas such as nuclear astrophysics, particle physics, nuclear medicine etc.

To overcome the nuclear barrier, the projectile need to have a minimum energy known as the threshold energy. Below the threshold energy the nuclear reaction would not happen. This is reflected in any yield curve. At lower energies, the reaction cross section is in general smaller and rises slowly with projectile energy and normally decreases after some peak cross-section point. As the incident energy increases, the nuclear cross section shows resonant peaks and valleys, corresponding to the excitation of specific energy levels in the target nucleus. The excitation function typically resembles a Gaussian bell curve and is mathematically described by a Breit–Wigner function [1-2].

The excitation function helps one to deduce important information about nuclear states, their properties and dynamics. It has applications in various fields, from nuclear astrophysics to nuclear medicine, and plays a vital role in the understanding of the fundamental nature of matter.

II. IMPORTANCE OF ^{26}AL NUCLEUS

In nature trace amount of the isotope ^{26}Al is present and for long it was thought to have occurred due to the interaction of the cosmic ray with argon by spallation. Initially it was thought that the half-life of this isotope was in the range of 6 to 7 seconds [3-4]. However, in early 50's there were already theoretical [5-6] and experimental [7-8] indications that this low lived state was not the ground state of ^{26}Al, rather the ground state should have a longer (10^4-10^6 years) half-life. First precise measurement of its half-life was done by Rightmere *et al* and it was found to be 7.14 x 10^5 years [9].

The long-lived nuclides (specially of light elements) are of prime importance to astrophysicists as they can be used to date and to calculate the exposure of celestial objects in cosmic rays. For this reason, ^{26}Al got much attention from the scientific community. The attention picked when ^{26}Al was found in Allende Meteorite [10] which is so far the largest (more than 2-ton fragments collected [11]) carbonaceous chondrite (i.e., some carbon compound that is rich in iron - containing about 24% iron) meteorite found to fall on Earth.

It fell in Chihuahua, Mexico on February 8, 1969, just a few months before Apollo 11 was supposed to land on the moon. The meteorite gave the scientists a unique opportunity to examine it using the tools developed to study lunar material. For these reasons, Allende is very often called "the best and most studied meteorite in history".

The estimated age of Allende meteorite is around 4.5 billion years. It is the most primitive known matter (about 30 million years older than planet Earth). Its age is frequently taken as the "age of the solar system" as it has been subject to the least mixing and remelting since the early stages of the formation of our solar system. One can rightly say that the meteorite had information about conditions prevailing during the early formation of our solar system. According to a study of a group of scientists in

California Institute of Technology in 1977, the time of explosion of the supernova (that is responsible for the birth of our solar system) within an accuracy of 2 million years can be found from the abundance of ^{26}Al isotope in Allende meteorite[12]. For this reason, often ^{26}Al is called a `natural clock'.

The results of HEAO-3 (The third High-Energy Astronomy Observatory, NASA) in the early 80's show that the total amount of ^{26}Al present in our galaxy is about (3.1±0.9) solar mass. The sources of ^{26}Al are supposed to be supernovae, novae, massive stars, Wolf-Rayet stars, red giants, and super-massive stars. The European Space Agency's Integral satellite's recent data suggest that there are 1.9 supernovae collapse per century in our galaxy. Supernovae collapse could contribute up to 3-4% of the total amount of ^{26}Al in the interstellar matter [13]. Novae, massive stars, Wolf-Rayet stars, and other proposed sources can contribute only about 0.02 solar mass amount of ^{26}Al. This value is too low to explain the comparably huge amount of ^{26}Al detected by HEAO-3. So far, there is no satisfactory explanation for this discrepancy regarding the abundance of the isotope and one should think that interstellar nucleosynthesis is an ongoing process.

The radioactive isotope ^{26}Al decays to the daughter nucleus ^{26}Mg by electron capture or positron emission. The presence of ^{26}Al at the beginning of the formation of the galaxy has been unquestionably established by the discovery of its daughter isotope ^{26}Mg in primitive interstellar objects. If these interstellar objects contained ^{26}Al at the time they were formed and afterwards remained unchanged, the yield of the decay product (^{26}Mg) should not change and now should provide a record of the original ^{26}Al abundance. The ratio of ^{26}Mg excess to the stable ^{27}Al thus can be used to find out the original ^{26}Al/^{27}Al ratio. This ratio varies in objects that formed at different times and can thus be used as an astronomical clock.

In stars and galaxies, the reaction conditions are not similar to the laboratory conditions and hence the reaction rate/cross-section in stellar conditions should not be the same. Inaugural work regarding the production and decay of ^{26}Al in a hot stellar like environments dates back to 70's when Truran, in 1972, used a statistical model of nuclear reactions to estimate the nuclear reaction rates for those reactions for which no experimental data were available [14]. Because of the retardation of a direct radiative decay between the isomeric state ^{26m}Al and the ground state ^{26}Alg.s., these two levels are normally treated as different species in theory.

Thus, the metastable ^{26m}Al state and the longer lived ^{26}Alg.s. state need to be treated as separate components in the reaction network. This makes theoretical calculations more complex and challenging. This was pointed out in 1967 (and extended in 1975) by Fowler, Caughlan, and Zimmerman [15-16]. In 1974, de Neijs *et al.* found 47 resonances in their calculation of the ^{26}Mg(p,n)^{26}Al reaction in the proton energy range from 317 keV to 1716 keV [17]. They found that in almost all the cases, the decay of a resonance populated both the ground state and the metastable state. Only in a very few cases did the decay led to production of ^{26}Al predominantly in either its ground or metastable state. In 1980, Ward and Fowler [18] attempted to explain the formation and decay of this isotope in a hot stellar environment. Since then, several groups put their efforts in redesigning and expanding the original model of Ward and Fowler. Of these, the most important works were carried out by Coc *et al*. in 1999 [19], Gupta and Meyer in 2001 [20], and lately, by Oginni *et al.* [21] in 2011. In all the said works, attempts were made to evaluate the yield and the effective lifetime expected for ^{26}Al in a hot astrophysical scenario. With respect to the decay of ^{26}Al in a hot stellar scenario, probably the most detailed and advanced works were carried out by Gupta and Meyer.

Even though ^{26}Al is one of the most astrophysically important nuclei, there is lack of experimental data regarding its destruction processes. This is mainly due to the fact that ^{26}Al is a very rare isotope and is mainly produced from beam-dumps at various particle accelerators. Also, since ^{26}Al is radioactive, the preparation of a suitable target is not very easy. For these reasons, most experiments focus on the reverse reaction ^{26}Mg(p,n)^{26}Al. The advantage of this process is that it is well studied around the reaction threshold in literatures. The forward reaction rates can be determined from this reaction. This has a relatively low proton reaction threshold of only 4.97 MeV which is very much achievable for present day accelerators.

III. IMPORTANCE OF ^{26}MG(P,N)^{26}AL REACTION

The Q-value calculator [22] shows that the threshold for ^{26}Mg(p,n)^{26}Al reaction is about 4.97 MeV. The NNDC/EXFOR database [23] shows that only a few sets of data are available for the yield of this reaction. The first measurements were carried out King and Cheng in 1979 at proton energy from 5.3 MeV to 9.5 MeV[24] . Their measurement suggested that ‘cross-sections calculated according to the statistical theory could introduce substantial error into any predictions involving the production of ^{26m}Al or ^{26g}Al during a nucleosynthesis event.’

In 1980 Paul *et al.* measured the cross section in proton energy range from 5.2 to 6.7 MeV with the then new technique of accelerator mass spectroscopy [25] and found that ‘near threshold, the data resembled relatively closely the theoretical predictions, maybe being somewhat higher, whereas at higher energies the experimental values were low by as much as a factor of 4'.

Third measurement was done by Norman *et al.* [26] in 1981 in the proton energy range 4.99 MeV to 5.30 MeV. Skelton *et al.* carried out a more reliable measurement in 1987 with proton beam energy ranging from 4.97 MeV to 5.82 MeV[27]. All measurements showed some resonances at different energies as is normal for any yield curve. However, other than these four measurements, no further experimental data is available for this astrophysically important reaction. Also, there is no experimental data for the yield function for proton energy above 9.5 MeV.

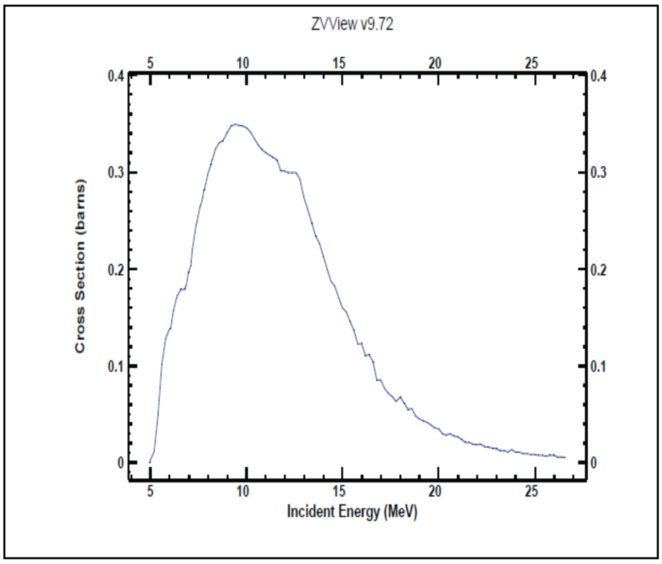

Fig. 1. Yield function from EMPIRE simulation

EMPIRE[28] is a very powerful open-source simulation tool that can be used for, among many other things, calculation of theoretical nuclear cross-section for a particular nuclear reaction. It incorporates various nuclear models. The projectiles can be a proton beam, a neutron beam, any ion (including heavy ions) or even a photon. The energy of the projectile can be varied from several eV to up to several hundred MeV. The simulation software is designed to account for the major nuclear reaction mechanisms including direct, pre-equilibrium and compound nucleus ones. The simulation tool also incorporates NNDC/EXFOR database in its library. In case experimental data is available for any nuclear reaction, in addition to the theoretical result, EMPIRE shows the experimental values too.

EMPIRE simulation was run on a 64-bit Ubuntu Linux distribution with projectile (proton beam) energy from 0 MeV to 30 MeV with a step of 10 keV. The simulation showed that below about 5.0 MeV the reaction cross-section was practically zero. This was in complete agreement with Q-tool calculation. As the projectile energy increased, the cross-section increased to a maximum of about 250 milli barn at a proton beam energy of 9.0 MeV. Above 10 MeV proton beam energy, the reaction cross-section started decreasing and above 24 MeV proton beam energy the cross-section was practically zero. Although some bumps in the yield curve gives hints of resonance structure at those energies, the yield curve produced by EMPIRE simulation failed to show clear resonance structure at specific energies as can be seen in Skelton data.

IV. CONCLUSION

Reaction cross-section for the reaction ^{26}Mg(p,n)^{26}Al at laboratory condition should differ from the cross-section in stellar conditions. Although there were several models to calculate reaction rate at stellar conditions (e.g., the model of Gupta-Mayar[20]), there is no experimental data as it had not been possible to simulate stellar conditions in laboratory previously. Present-day high-energy lasers can produce high intensity proton beams of energy of up to several hundred MeV. The beam is so intense that for a very short period of time (ns-ps) it will simulate stellar condition and in very near future it might be possible to study the reaction ^{26}Mg(p,n)^{26}Al in stellar conditions. EMPIRE simulation results at high proton beam energy will prove to be useful in such case.

REFERENCES

[1] G. Breit and E. Wigner, “Capture of Slow Neutrons,” Physical Review, vol. 49, no. 7, p. 519, Apr. 1936, doi: 10.1103/PhysRev.49.519.

[2] A. R. Bohm and Y. Sato, “Relativistic resonances: Their masses, widths, lifetimes, superposition, and causal evolution,” Physical Review D - Particles, Fields, Gravitation and Cosmology, vol. 71, no. 8, pp. 1–22, Apr. 2005, doi: 10.1103/PHYSREVD.71.085018/FIGURES/1/MEDIUM.

[3] M. G. White, L. A. Delsasso, J. G. Fox, and E. C. Creutz, “Short-Lived Radioactivities Induced in Fluorine, Sodium and Magnesium by High Energy Protons,” Physical Review, vol. 56, no. 6, p. 512, Sep. 1939, doi: 10.1103/PhysRev.56.512.

[4] O. R. Frisch, “Induced Radioactivity of Sodium and Phosphorus,” Nature 1934 133:3367, vol. 133, no. 3367, pp. 721–722, 1934, doi: 10.1038/133721b0.

[5] P. Stähelin, “The 0$^+$ States of the Light Odd-Odd Nuclei,” Physical Review, vol. 92, no. 4, p. 1076, Nov. 1953, doi: 10.1103/PhysRev.92.1076.2.

[6] S. A. Moszkowski and D. C. Peaslee, “Isotopic Spin and Odd-Odd N=Z Nuclei,” Physical Review, vol. 93,no.3,p.455,Feb.1954,doi: 10.1103/PhysRev.93.455.

[7] J. C. Kluyver, C. Van Der Leun, and P. M. Endt, “Ground State of Al^{26}” Physical Review, vol. 94, no. 6, p. 1795, Jun. 1954, doi: 10.1103/PhysRev.94.1795.

[8] R. Montalbetti, L. Katz, and J. Goldemberg, “Photoneutron Cross Sections,” Physical Review, vol. 91,no.3,p.659,Aug.1953,doi: 10.1103/PhysRev.91.659.

[9] R. A. Rightmire, T. P. Kohman, and H. Hintenberger, “Über Die Halbwertszeit Des Langlebigen ^{26}Al,” Zeitschrift fur Naturforschung - Section A Journal of Physical Sciences, vol. 13, no. 10, pp. 847–853, Oct. 1958, doi: 10.1515/ZNA-1958-1010/PDF.

[10] T. Lee, D. A. Papanastassiou, and G. J. Wasserburg, “Correction [to ‘Demonstration of ^{26}Mg excess in Allende and evidence for ^{26}Al’],” Geophys Res Lett, vol. 3, no. 2, pp. 109–112, Feb. 1976, doi: 10.1029/GL003I002P00109.

[11] E. Jarosewich, R. S. Clarke, and J. N. Barrows, “The Allende Meteorite Reference Sample” SMITHSONIAN CONTRIBUTIONS TO THE EARTH SCIENCES NUMBER 27.

[12] “Meteorites lend clues to solar system’s origin (2019, December 17) retrieved 22 May 2023 from https://phys.org/news/2019-12-meteorites-clues-solar.html.”

[13] “R. Walter and A. Maeder; Astron. Astrophys. 218, p123-130 (1989).”.

[14] “J. W. Truran; Ap. Space Sci. 18, p306 (1972).”.

[15] W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, “Thermonuclear Reaction Rates,” https://doi.org/10.1146/annurev.aa.05.090167.002521, vol. 5, no. 1, pp. 525–570, Nov. 2003, doi: 10.1146/ANNUREV.AA.05.090167.002521.

[16] W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, “Thermonuclear Reaction Rates, II,” https://doi.org/10.1146/annurev.aa.13.090175.000441, vol. 13, no. 1, pp. 69–112, Nov. 2003, doi: 10.1146/ANNUREV.AA.13.090175.000441.

[17] E. O. De Neijs, M. A. Meyer, J. P. L. Reinecke, and D. Reitmann, “The energy levels of ^{26}Al,” Nucl Phys A, vol. 230, no. 3, pp. 490–508, Sep. 1974, doi: 10.1016/0375-9474(74)90152-3.

[18] R. A. Ward and W. A. Fowler, “Thermalization of long-lived nuclear isomeric states under stellar conditions,” ApJ, vol. 238, pp. 266–286, May 1980, doi: 10.1086/157983.

[19] A. Coc, M. G. Porquet, and F. Nowacki, “Lifetimes of ^{26}Al and ^{34}Cl in an astrophysical plasma,” Phys Rev C, vol. 61, no. 1, p. 015801, Dec. 1999, doi: 10.1103/PhysRevC.61.015801.

[20] S. S. Gupta and B. S. Meyer, “Internal equilibration of a nucleus with metastable states: ^{26}Al as an example,” Phys Rev C, vol. 64, no. 2, p. 025805, Jul. 2001, doi: 10.1103/PhysRevC.64.025805.

[21] B. M. Oginni, C. Iliadis, and A. E. Champagne, “Theoretical evaluation of the reaction rates for Al^{26}(n,p)^{26}Mg and Al^{26}(n,α)^{23}Na,” Phys Rev C Nucl Phys, vol. 83, no. 2, p. 025802, Feb. 2011, doi: 10.1103/PHYSREVC.83.025802/FIGURES/13/MEDIUM.

[22] https://www.nndc.bnl.gov/qcalc/.

Last accessed: 22 May 2023, 12:00 pm GMT.

[23] https://www-nds.iaea.org/exfor/.

Last accessed: 22 May 2023, 12:00 pm GMT.

[24] J. D. King and C. W. Cheng, “Cross sections for the ^{26}Mg(p,n)^{26g}Al(7.3×10^{5}yr) and ^{26}Mg(p,n)^{26m}Al(6.35 s)reactions,” https://doi.org/10.1139/p79-036, vol. 57, no. 2, pp. 286–291, Feb. 2011, doi: 10.1139/P79-036.

[25] M. Paul, W. Henning, W. Kutschera, E. J. Stephenson, and J. L. Yntema, “Measurement of the ^{26}Mg(p,n)^{26}Al$_{g}$(7.2 ×10^{5}) yr cross section via accelerator mass spectrometry,” Physics Letters B, vol. 94, no. 3, pp. 303–306, Aug. 1980, doi: 10.1016/0370-2693(80)90883-7.

[26] E. B. Norman et al., “Cross Sections for the ^{26}Mg+p - ^{26}Al+n Reactions,” ApJ, vol. 251, p. 834, Dec. 1981, doi: 10.1086/159527.

[27] R. T. Skelton, R. W. Kavanagh, and D. G. Sargood, “^{26}Mg(p,n)^{26}Al and ^{23}Na(α,n)^{26}Al reactions” Phys Rev C, vol. 35, no. 1, p. 45, Jan. 1987, doi: https://doi.org/10.1103/PhysRevC.35.45.

[28] M. Herman et al., “EMPIRE: Nuclear Reaction Model Code System for Data Evaluation,” Nuclear Data Sheets, vol. 108, no. 12, pp. 2655–2715, Dec. 2007, doi: 10.1016/J.NDS.2007.11.003.